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Evaluating The Relation of Trace Fracture Inclination and Sound Pressure Level and Time-of-flight QUS Parameters Using Computational Simulation

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Abstract

Bone healing is a complex process that stars after the occurrence of a fracture to restore bone optimal conditions. The gold standards for bone status evaluation are the dual energy X-ray absorptiometry and the computerized tomography. Ultrasound-based technologies have some advantages as compared to X-ray technologies: nonionizing radiation, portability and lower cost among others. Quantitative ultrasound (QUS) has been proposed in literature as a new tool to follow up the fracture healing process. QUS relates the ultrasound propagation with the bone tissue condition (normal or pathological), so, a change in wave propagation may indicate a variation in tissue properties. The most used QUS parameters are time-of-flight (TOF) and sound pressure level (SPL) of the first arriving signal (FAS). In this work, the FAS is the well known lateral wave. The aim of this work is to evaluate the relation of the TOF and SPL of the FAS and fracture inclination trace in two stages of bone healing using computational simulations. Four fracture geometries were used: normal and oblique with 30, 45 and 60 degrees. The TOF average values were 63.23 μs, 63.14 μs, 63.03 μs 62.94 μs for normal, 30, 45 and 60 degrees respectively and average SPL values were -3.83 dB -4.32 dB, -4.78 dB, -6.19 dB for normal, 30, 45 and 60 degrees respectively. The results show an inverse pattern between the amplitude and time-of-flight. These values seem to be sensible to fracture inclination trace, and in future, can be used to characterize it.

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Keywords:Cortical bone; fracture healing; computation simulations; quantitative ultrasound

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1. Introduction

Fracture healing is a complex process that stars after the occurrence of a fracture, aiming at the total reestablishment of bone normal properties (Phillips, 2005). This is an important subject, and has received a lot of attention from the scientific community. The gold standard methods for evaluating bone status are the dual X-ray absorptiometry (DEXA) and computerized tomography (CT) (Laugier, 2008). Ultrasound-based technologies have some advantages as compared with those described: absence of ionizing radiation, portability, and in general, lower cost, among others (Laugier, 2008). Quantitative ultrasound (QUS) has been proposed in literature to follow up the healing process. It is based on the fact that the ultrasonic field depends on the medium properties; so, a change in the wave propagation may suggest a properties variation. For biological media, this variation can indicate a disease. There are many QUS parameter. Among them, time-of-flight (TOF) and sound pressure level (SPL) of the lateral (or head) wave have been widely used (Laugier, 2008). The first is the time between the emission and reception of the signal (according to some criterion) and the second is a relative measure of the local pressure. It is not easy to distinguish the lateral wave from other signals, however, when certain conditions are respected (Bossy et al, 2007), this wave is the first arriving signal (FAS). Given this scenario, the aim of this work is to evaluate the relation of the TOF and SPL of the FAS and fracture inclination trace in two stages of bone healing by computational simulations.

2. Methods

2.1. Lateral wave

Using Huygens' Principle, a simple explanation of the lateral wave formation processes follows (Bossy, 2002): when a spherical wavefront impinges a fluid-solid interface, it is partially reflected and refracted. During this process, the point that connects these two wavefronts is moving to the right and the line that connects it to the source makes an angle θ with the axis normal to the interface. When this angle reaches the critical one, given by the Snell-Descartes' Law, a phenomenon closely related to total reflection takes place (assuming the wave speed in the medium 2 greater than medium 1) and the theory predicts the existence of a linear wavefront that connects the refracted and reflected wavefronts. This wave is called lateral wave or head wave.

2.2. Computational simulation design and signal processing

The axial transmission (AT) wave propagation models were performed in the software Wave2000® (Cyberlogic, New York, NY), which solves the 2-D wave equation using the time domain finite difference method (FDTD). In all simulations, the time and space discretization were 0.00436 µs e 0.2 mm, respectively.

A simple code was implemented in MATLAB® (MathWorks Inc., Natick, MA) for the FAS first peak detection (TOF and amplitude criterion of estimation). This routine extracts the coordinates of this point (time, amplitude). The algorithm is based on the concept of derivative, which assumes a sign change when it crosses a maximum or a minimum. When the signal contains noise, it is necessary a filtering, or the algorithm may fail.

A rectangular region with 180 x 50 mm was defined as the simulation domain. Inside this region, was placed a plate with 180 x 10 mm (stage A, B and reference) and a Gaussian shape volume (Stage B), whose mimic the cortical bone and bone callus, respectively. One source and 32 receivers with 3 mm width were positioned at 15 mm above the plate. The distance between the source and the first receiver is 52 mm, and, among the receivers is 1 mm. A scheme may be seen in Fig 1. The pulse generated by the source was a sine modulated Gaussian with duration of 3µs and center frequency of 1 MHz; the receivers output were the average pressure at transducer face.

Three geometries were modeled: stage A, stage B and reference. The first represents the moment after the bone fracture occurs. This is the start of healing process, where blood fills the fracture gap and the region around it, serving as a callus template and as a signal, for the recruitment of mesenquimal steam cells (MSC). Stage B models an instant between the hard callus formation and complete healing. The hard callus was modeled by a Gaussian with 40 mm width and 3 mm height. The last stage is the intact bone, used as a reference for the calculus of SPL. Here, water mimics the blood (Stage A) and is used as a coupling medium (Stage A, B and reference), and, as described above, the bone is mimicked by the plate. Fig 2 shows the geometries.

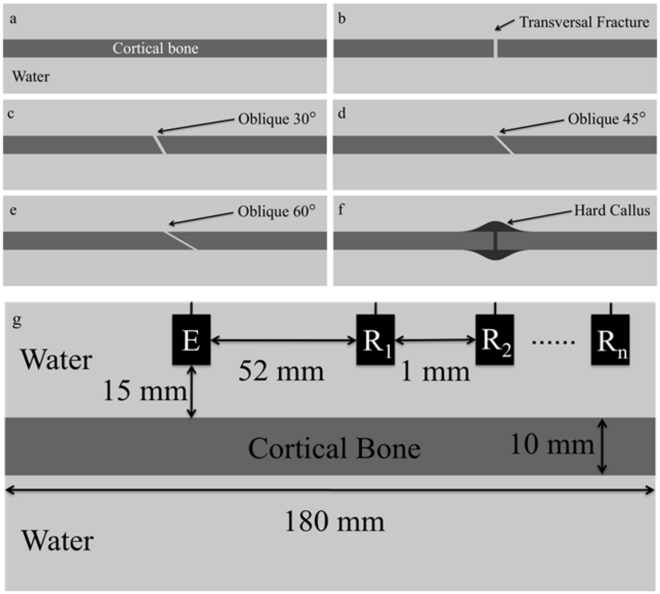

Fig. 1. (a) Reference stage: intact bone; (b) stage A: transversal fracture; (c) stage A: oblique 30º; (d) stage A: oblique 45º (e) stage A: oblique 60º; (f) stage B: transversal fracture; (g) general scheme of the axial transmission models: source (E) and receiver (R) with 3 mm width positioned 15 mm above the cortical plate (180 x 10 mm) surrounded by water. The distance among the receivers is 1 mm.

2.3. Material Properties

Table 1 shows the acoustical and mechanical properties of the materials used in the simulations. The water properties are from the software library. The others were taken from Gheduzzi et al (2008).

Table 1. Material properties: density (ρ), Young modulus (E), Poisson's ration (σ), longitudinal (V_L) and shear (V_T) velocity, respectively (Gheduzzi, 2009).

Material	ρ (kg m^{-3})	E (Gpa)	σ	V_L	V_T
Hard Callus	1600	5	0.3	2050	1095
Cortical Bone	1850	16.45	0.37	4000	1800
Water	1000	Library	Library	1500	0

3. Results

Fig. 2 shows the SPL and TOF curves for the stages A and B. In Table 2 are the SPL and TOF values at the last receiver.

Table 2. SPL and TOF values at last receiver for both stages.

Fracture geometry	SPL (dB)		TOF (µs)	
-	Stage A	Stage B	Stage B	Stage B
Transversal	-5.64	-2.02	63.43	63.03
Oblique 30º	-6.42	-2.22	63.30	62.99
Oblique 45º	-6.93	-2.63	63.17	62.90
Oblique 60º	-8.87	-3.52	63.03	62.86

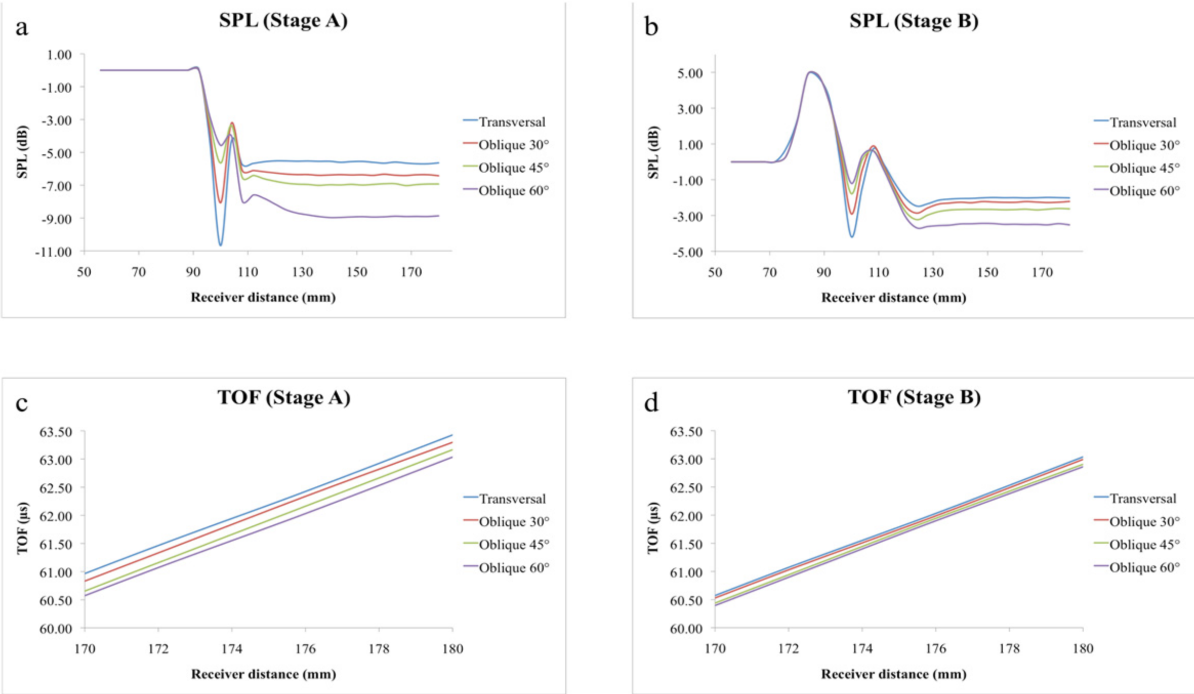

Fig. 2. (a) SPL curves for stage A; (b) SPL curves for stage B; (c) TOF curves for stage A; (d) TOF curves for stage B.

4. Discussion and conclusion

The relation between the fracture trace angle and the QUS parameters SPL and TOF of two healing stages using numerical models was evaluated. The SPL curves show a similar behavior for all fracture geometries at each stage. The main differences are the amplitude fall due to discontinuity, and the final equilibrium value. In both stages, the smallest amplitude was for the oblique fracture (60º angle), and the highest was the transversal one. The SPL decreases with angle increasing (Table 2). The two stages differ by the hard callus effect, which leads to a SPL gain.

The TOF curves shapes are similar. The difference is in the final values (Table 2). The oblique fracture with inclination of 60º always has the shortest TOF and for transversal fracture, it reaches its biggest value. These results have shown the possibility to use TOF to discriminate different fractures inclination, at least, in theory for both stages. It seems to exist a pattern between the inclination and parameters SPL and TOF to be explored in the future.

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References

Bossy, E., Talmant, M., Laugier, P., 2002. Effect of Bone Cortical Thickness on Velocity Measurements Using Ultrasonic Axial Transmission: A 2D Simulation Study. Journal of Acoustical Society of America 112, 297-307.

Gheduzzi, S., Dodd, S. P., Milles, A. W., Humphrey, V. F., Cunningham, J. L., 2009. Numerical and Experimental Simulations of the effect of Long Bone Fracture Healing Stages on Ultrasound Transmission Across an Idealized Fracture. J Acoustical Society of America 126, 887-894

Laugier, P., 2008. Instrumentation for in Vivo Ultrasonic Characterization of Bone Strength. IEEE T on UFFC 55, 1179-1196.

Phillips, A. M., 2005. Overview of Fracture Healing Cascade. Injury 36, 5-7